GRAVITATIONAL EXPERIMENT BELOW 1 MILLIMETER AND COMMENT ON SHIELDED CASIMIR BACKGROUNDS FOR EXPERIMENTS IN THE MICRON REGIME

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We present the status of an experimental test for gravitational strength forces below 1 mm. Our experiment uses small 1 kilohertz oscillators as test masses, with a stiff counducting shield between them to suppress backgrounds. At the present sensitivity of approximately 10^3 times gravitational strength, we see no evidence for new forces with interaction ranges between 75 μm and 1 mm. While the Casimir background is not expected to be significant at this range, an extension of the shielding technique we employ may be useful for reducing this background in experiments below a few microns. We describe a possible implementation.

1 Introduction

Experimental searches for new macroscopic forces have only marginally explored the distance range under 1 mm and there is little knowledge of gravity itself in this range. The sub-millimeter region is of profound and rapidly increasing experimental interest, given a number of recent predictions of new forces from a rich variety of modern theories of fundamental interactions.

The existing experimental limits on new forces at short distances are defined by classical gravity measurements and Casimir force measurements,[1] as shown in Fig. 2. From the figure, in which the strength α of a hypothetical new force relative to gravity is plotted versus the Yukawa range λ, the published experimental limits allow for forces in nature several million times stronger than gravity over ranges as great as 100 μm.

Also shown in Fig. 2 are theoretical predictions of new effects in this regime.[2] Most notable is the line indicating Yukawa corrections to the inverse square law which arise from compact extra dimensions.[3] Corrections are also predicted from massive scalars in string theories, such as Moduli and Dilatons.[4] The other predictions shown are motivated by the Cosmological Constant Problem[5] and the Strong CP Problem of QCD.[6]

Since the summer of 1997, we have been constructing an experiment to explore the sub-centimeter regime. The approach uses a high-frequency technique, departing from the torsion balance method which was used in all measurements defining the current limits.

2 Status of the Experiment

2.1 Design Overview

If all dimensions of experimental test masses of a gravitational experiment are scaled by the same factor D, Newtonian attraction varies as D^4. At small separations, signals from mass–coupled forces become very weak. At the same time, background effects such as surface forces increase rapidly.

Our experimental approach is shown in Fig. 1 (see Ref. 1 and the last paper of Ref. 3 for more detail). Planar test mass geometry is chosen to concentrate as much mass as possible at the scale of interest. The test masses consist of 200 μm thick tungsten oscillators. The detector is driven by the source mass on resonance near 1 kHz. At this frequency it is possible to construct simple, passive vibration isolation stacks sufficient to suppress the acoustic coupling of the test masses though the apparatus. Detector oscillations are read out with a capacitive transducer and lock-in amplifier. The entire apparatus is enclosed in a vacuum chamber and operated at 10^{-7} torr to reduce the acoustic coupling between the test masses though the residual gas in between them.

The principal backgrounds in addition to the acoustic backgrounds arise from electrostatic and magnetic forces. Electrostatic forces, as well as acoustic coupling through the residual gas, are suppressed with a stiff conducting shield, consisting of a 75 μm thick quartz window plated with gold, suspended between the test masses. Magnetic backgrounds have so far been avoided with the exclusive use of non-magnetic materials for the construction of the apparatus. If the need arises, in-situ imaging of magnetic contaminants on the test masses is possible.

If all of these backgrounds can be sufficiently reduced, the limiting background of this experiment will be thermal noise due to dissipation in the detector mass. The experiment is therefore being carried out in two phases. A preliminary, room–temperature version of the experiment is now in operation and nearing the practical limit of its sensitivity. The final version of the experiment will be cooled to liquid Helium temperatures for greater sensitivity.

2.2 Current Sensitivity

A signal from a new effect can be modeled as the force on the detector mass due to a Yukawa interaction with the source mass. This force is given by:

$$F_Y(t) = 2\pi\alpha G\rho_s\rho_d A\lambda^2 \exp{(-d(t)/\lambda)}[1-\exp{(-t_s/\lambda)}][1-\exp{(-t_d/\lambda)}], \quad (1)$$

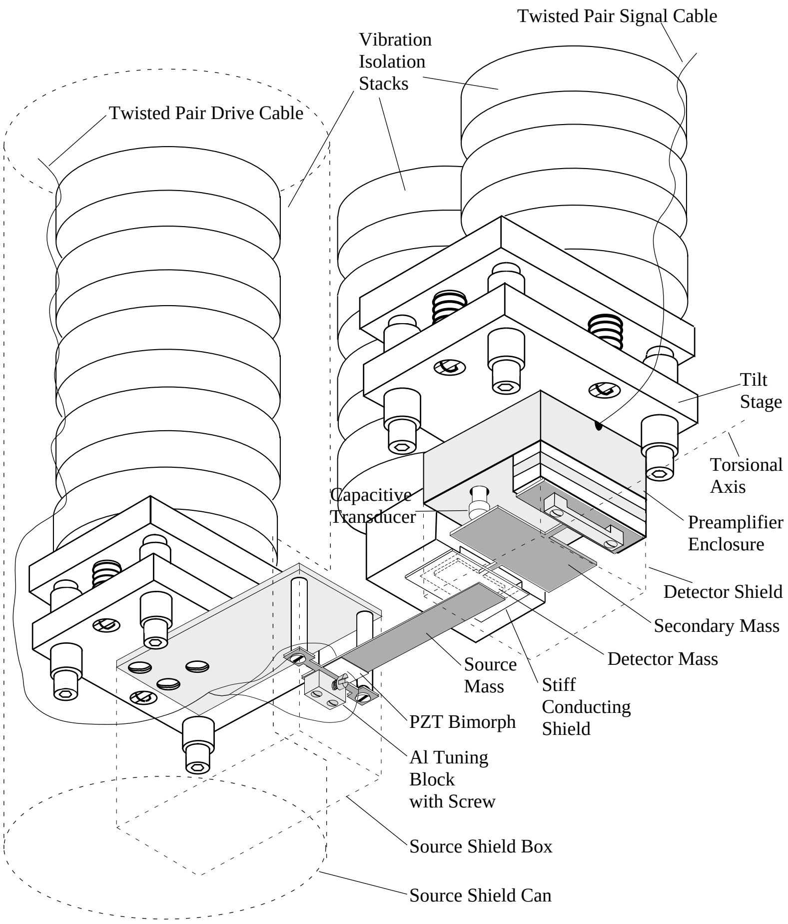

Figure 1. Central components of the apparatus.

where $d(t)$ is the separation between the test masses, ρ_s and ρ_d are the source and detector mass densities, and t_s and t_d are the thicknesses. This would be an exact expression if either plate had area A and the other had infinite area, but for the real geometry there are small edge corrections, which we do not consider. For values of these parameters typical for our experiment, this force is approximately 2×10^{-14} N, for $\alpha = 1$ and $\lambda = 100\ \mu$m.

The rms thermal noise force is found from the mechanical Nyquist theorem to be:

$$F_T = \sqrt{\frac{4kT}{\tau}\left(\frac{m\omega}{Q}\right)}, \tag{2}$$

where m is the mass of the small rectangular section of the detector oscillator, ω is the resonant frequency, Q is the detector quality factor, T is the temperature and τ is the measurement integration time. For typical Q values of our tungsten detector mass (2.5×10^4), a temperature of 300 K, and an integration time of 1000 s, this force (and hence the current sensitivity of our experiment) is about 4×10^{-14} N.

In April 2000, the room temperature experiment became fully operational for the first time. No signal was observed above the detector thermal noise over the entire integration time of 1800 s. Setting the ratio of Eqs. 1 and 2 to unity and solving for α, we infer the limits on the Yukawa parameters as shown in Fig. 2.

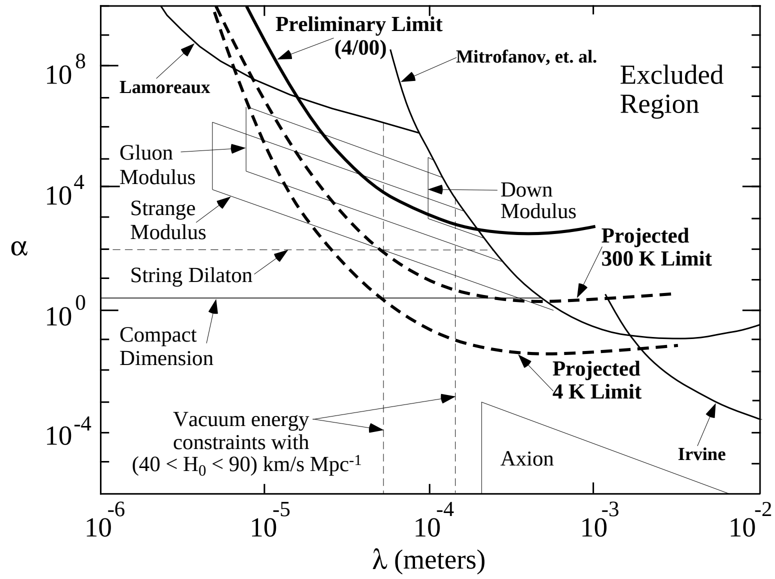

Figure 2. Parameter space for Yukawa-type forces in which the strength relative to gravity (α) is plotted versus the range (λ). Limit curves from published experiments are shown along with theoretical predictions of new phenomena in this regime. The bold lines indicate the current (solid) and projected (dashed) sensitivities of our experiment.

2.3 Recent Improvements

For the April run, thermal drifts of the detector resonance limited the integration time to 1800 s. Furthermore, a poor match between source and detector resonant frequencies limited the source mass amplitude to roughly 0.5 μm. Since that run we have installed temperature control, allowing for much longer integration times. We have tuned the source mass such that amplitudes greater than 50 μm on resonance are now possible. Also, we have fabricated a new shield from 50 μm thick sapphire, making smaller separations possible. With these improvements, we expect the room temperature experiment to attain the sensitivity represented by the upper dashed curve in Fig. 2.

The final cryogenic version of the experiment is under development. Assuming the backgrounds can be controlled, we expect this experiment to reach gravitational strength at 50 μm, as represented by the lower dashed curve in Fig. 2.

3 Shielded Casimir Background in the Micron Regime

Session PT6 at MG9 featured discussions of experimental searches for new forces in the sub-micron regime, where the Casimir background is expected to dominate. A series of Casimir force measurements has been carried out in this regime using an AFM,[7] and limits on new forces down to 10 nm have been derived from these experiments.[8] So far, the limits are many orders of magnitude stronger than gravity, motivating the design of dedicated searches for new forces. One proposal in this regime is the "iso-electronic" technique of Fischbach and Krause.[9]

The Casimir background is not expected to be significant in our existing experiment. However, an extension of the shielding technique we employ may be useful for AFM–type searches in experiments near 1 μm.

Our idea is illustrated in Fig. 3. A probe at a distance D above a flat gold sample is scanned over regions of alternating depth D and $2D$. The horizontal dimensions of all probe and sample features are taken to be much larger than D. The gold sample is backed by a low–density dielectric substrate which for the purposes of this study we take to be vacuum.

Due to the finite penetration depth of the sample metal, above a certain scale D we expect the Casimir force between the probe and either thickness region of the sample to be essentially equal. While mass–coupled forces between probe and sample may be much more feeble, for them we do not expect a similar equalization across the thickness boundaries.

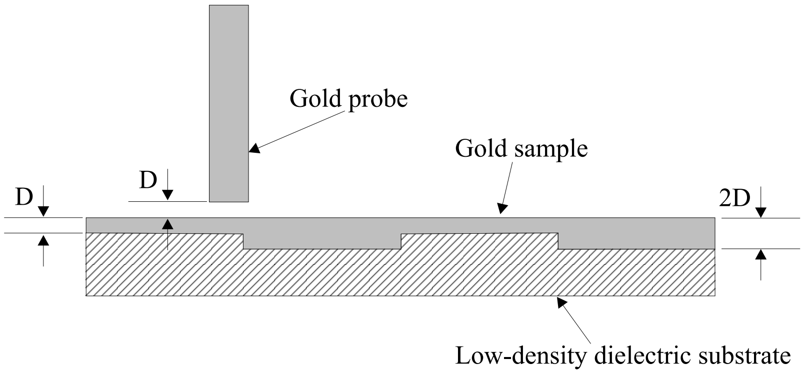

Figure 3. Idealized experimental geometry. Horizontal dimensions of all features are taken to be much larger than D.

We have calculated the Casimir forces for the geometry in Fig 3. We use the method developed by A. Lambrecht and S. Reynaud,[10] ignoring the effects of surface roughness and finite temperature. We employ a Drude model for the gold probe and sample, using a plasma frequency of $\omega_P = 1.4 \times 10^{16}$ rad/s and relaxation parameter of $\gamma = 5.3 \times 10^{13}$ rad/s in Eq. 16 of Ref. 10.

Setting the plate separation L in Eq. 9 of Ref. 10 equal to D, we then use Eqs. 12, 9, and 4 of that reference to calculate the difference in the Casimir force between the probe and sample regions of thickness D and $2D$: $\Delta F_C = F_C^{2D} - F_C^{D}$. We assume the probe to have infinite thickness. As a preliminary check, we set the sample thickness equal to infinity and note that our results for the Casimir reduction factor η_F agree with those of Fig. 6 of Ref. 10 to within 5%.

We then compute the difference in the Yukawa force for the same geometry, using $\alpha = 1$ and $\lambda = D$: $\Delta F_Y = F_Y^{2D} - F_Y^{D}$. The ratio $\Delta F_Y / \Delta F_C$ is shown in Fig. 4 as a function of D for 10^{-8} m $< D < 5 \times 10^{-6}$ m. We note that these results change by less than 1% as we vary the limits of integration [10^8–10^{20} rad/s] by an order of magnitude.

The steep rise in the curve occurs when the scale D approaches the plasma wavelength we have used for gold (about 1.4×10^{-7} m), at which point the shielding increases rapidly. For the idealized geometry and conditions we have assumed, Fig. 4 implies that a gravitational–strength Yukawa force becomes distinguishable from the Casimir background as the probe is scanned across the thickness boundary at a scale D of about 3 μm.

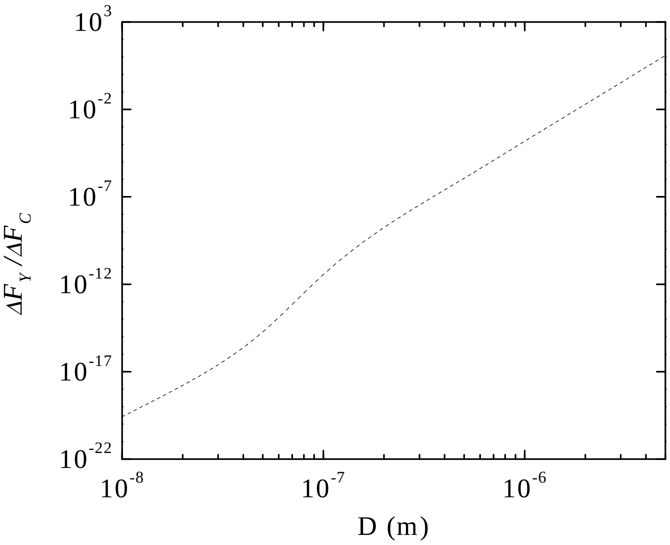

Figure 4. Scale dependence of variation of Yukawa force with $\alpha = 1$, $\lambda = D$, relative to variation of Casimir Force as probe is scanned from over sample region of thickness D to region of thickness $2D$.

Acknowledgments

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